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The effect of bioenergy expansion: Food, energy, and environment

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ABSTRACT

The increasing prices and environmental impacts of fossil fuels have made the production of biofuels to reach unprecedented volumes over the last 15 years. Given the increasing land requirement for biofuel production, the assessment of the impacts that extensive biofuel production may cause to food supply and to the environment has considerable importance. Agriculture faces some major inter-connected challenges in delivering food security at a time of increasing pressures from population growth, changing consumption patterns and dietary preferences, and post-harvest losses. At the same time, there are growing opportunities and demands for the use of biomass to provide additional renewables, energy for heat, power and fuel, pharmaceuticals and green chemical feedstocks. Biomass from cellulosic bioenergy crops is expected to play a substantial role in future energy systems. However, the worldwide potential of bioenergy is limited, because all land is multi-functional and land is also needed for food, feed, timber, and fiber production, and for nature conservation and climate protection. Furthermore, the potential of bioenergy for climate change mitigation remains unclear due to large uncertainties about future agricultural yield improvements and land availability for biomass plantations. Large-scale cultivation of dedicated biomass is likely to affect bioenergy potentials, global food prices and water scarcity. Therefore, integrated policies for energy, land use and water management are needed. As biomass contains all the elements found in fossil resources, albeit in different combinations, therefore present and developing technologies can lead to a future based on renewable, sustainable and low carbon economies. This article presents [1] risks to food and energy security [2] estimates of bioenergy potential with regard to biofuel production, and [3] the challenges of the environmental impact.

Contents

Abbreviations: GHG, Greenhouse GasEJ Exajoule; TOE, ton oil equivalent; GJ, Giga Joule; FFV, flex-fuel vehicle; LUC, land use change; DDGS, dried distillers grains with solubles; CGF, corn gluten feed; CGM, corn gluten meal; EPA, Environmental Protection Agency; RED, Renewable Energy Directive

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1. Introduction

This paper provides a comprehensive review on global bioenergy, especially biofuels production and potentials, including different feedstock sources, technological paths, financing and trade. The impacts on food production, environment and land requirements are also discussed. It is concluded that the rise in the use of biofuels is inevitable and that international cooperation, regulations, certification mechanisms and sustainability criteria must be established regarding the use of land and the mitigation of environmental impacts caused by biofuel production. Finally, the impact of substitution of traditional animal feed with co-products of biofuel production on the land use of feedstocks is also addressed.

The world's population continues to grow and, over the next 40 years, agricultural production will have to increase by some 60% [1]. Meanwhile a quarter of all agricultural land has already suffered degradation, and there is a deepening awareness of the long term consequences of a loss of biodiversity with the prospect of climate change. Higher food, feed and fiber demand will place an increasing pressure on land and water resources, whose availability and productivity in agriculture may themselves be under threat from climate change. The additional impact on food prices of higher demand for crops as energy feedstock is of real concern. Since biomass can substitute for petrochemicals too, higher oil prices will trigger new non-energy demands on bioresources as well. In the last 35 years global energy supplies have nearly doubled but the relative contribution from renewables has hardly changed at around 13% [2]. Global energy demand is increasing, as is the environmental damage due to fossil fuel use. Continued reliance on fossil fuels will make it very difficult to reduce emissions of greenhouse gases that contribute to global warming. Bioenergy currently provides roughly 10% of global supplies and accounts for roughly 80% of the energy derived from renewable sources [2]. The "new" renewables (e.g., solar, wind, and biofuel) have been growing fast from a very low base. Although their contribution is still a marginal component of total global renewable energy supply, they are continuously growing. Bioenergy was the main source of power and heat prior to the industrial revolution. Since then, economic development has largely relied on fossil fuels. A major impetus for the development of bioenergy has been the search for alternatives to fossil fuels, particularly those used in transportation.

In the past, burning fossil fuels, deforestation and other human activities have released large amounts of greenhouse gases into the atmosphere. Today, almost all of the commercially available biofuels are produced from either starch- or sugar-rich crops (for bioethanol), or oilseeds (for biodiesel). Recent research has found that these bioenergy sources have their drawbacks [3,4] and turned attention to the use of ligno-cellulosic feedstocks, such as perennial grasses and short rotation woody crops for bioenergy production [5,6]. Removing CO_2 from the atmosphere (negative emissions) implies that human-induced uptake of CO_2 would have to be larger than the amount of human-induced GHG emissions. One of the few technologies that may result in negative emissions is the combination of bioenergy and carbon capture and storage (CCS) [7].

Based on this diverse range of feedstocks, the technical potential for biomass is estimated in the literature to be possibly as high as 1500 EJ/year by 2050 [8]. Estimates of global primary bioenergy potentials available around 2050 published in the last 5 years span range from 30 to 1300 EJ/year [9,10]. Dornburg et al. [11] analyzed a number of projections and pointed out that studies on the potential of biomass as an energy source are in the range of 0–1500 EJ. A sensitivity analysis conducted by Dornburg et al. narrows that range to approximately 200–500 EJ/year in 2050 when taking into consideration water limitations, biodiversity protection and food demand. Recently, the IPCC Special Report on Renewable Energy [12] reported a huge range of 50–500 EJ/year. Also important are the results reached in the Global Energy Assessment [13], which concludes on a potential equal to 160–270 EJ/year in 2050. Such a wide range is due to differences in methodology as well as assumptions on crop yields and available land. The higher value resulting from an optimistic approach assumes a highly developed agricultural system, the lower is the result of a pessimistic approach with high population growth and extreme measures to avoid biodiversity loss [14]. Batidzirai et al. [15] present a very comprehensive overview of bioenergy potentials, also discussing the different types of potential. The differences in bioenergy resource assessment estimates are due to the broad variety of approaches, methodologies, assumptions and datasets.

The total annual aboveground net primary production (the net amount of carbon assimilated in a time period by vegetation) on the Earth's terrestrial surface is estimated to be about 30–35 Gt carbon of biomass growth with a gross energy value of 1100–1260 EJ/year, assuming an average carbon content of 50% and 18 GJ/t average heating value, which can be compared to the current world primary energy supply of about 550 EJ/year [16,17]. All harvested biomass used for food, fodder, fiber and forest products, when expressed in equivalent heat content, equals 219 EJ/year. The global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) corresponds to about 60 EJ/year. In order to produce that biomass, humans affect or even destroy roughly another 70 EJ/year of biomass in the form of plant parts not harvested and left on the field and biomass burned in anthropogenic vegetation fires. The global industrial roundwood production corresponds to 15 to 20 EJ/year [17–19]. Hence, some 800–900 EJ/year worth of biomass currently remains in the aboveground compartment of global terrestrial ecosystems. In order to meet their biomass demand, humans affect approximately three quarters of the Earth's ice-free land surface with huge implications for ecosystems and biodiversity [19]. However, most biomass supply scenarios that take into account sustainability constraints, indicate an annual potential of between 200 and 500 EJ/year [2]. In other energy scenarios, bioenergy use is projected to be in the order of 150–400 EJ in the year 2100 [20].

Large-scale bioenergy production and associated additional demand for irrigation may further intensify existing pressures on water resources [21]. In tropical and sub-tropical developing countries deforestation happens due to land clearing for new crop- and pasture land but also due to the use of biomass for traditional heat and energy production. Forests are a major storage of carbon [22], so there is an adverse impact when forest carbon is released for the purpose of bioenergy production [23]. But deforestation not only removes a carbon sink, it is also regarded as the greatest threat to terrestrial biodiversity as forests are the most

biologically diverse terrestrial ecosystems [24]. Therefore, nature conservationists support forest conservation for climate change mitigation [25,26]. In order to assess the impacts of forest conservation on bioenergy potentials based on the rationale that bioenergy is not carbon neutral Popp et al. (2011) have linked a global dynamic vegetation and water balance model, a global land and water use model, and a global energy–economy–climate model [27]. In the scenario without forest conservation, bioenergy demand increases up to about 300 EJ in 2095 with a demand of about 100 EJ in 2055. For this specific scenario, biomass from dedicated bioenergy crops will contribute 25% to the total global demand for primary energy carriers. However, forest exclusion for the purpose of biodiversity conservation and climate change mitigation affects the availability of cost-efficient biomass for energy production significantly. The amount of bioenergy supplied is reduced to about 70 EJ in 2055 and 270 EJ in 2095 in the scenario with 100% forest conservation [27].

The sustainability of bioenergy has been discussed widely in recent years. Sustainability criteria have been introduced, mainly focusing on direct effects of the production chain of bioenergy products. But bioenergy may cause significant indirect effects in other production systems too [28]. The displacement of agricultural production has been discussed extensively in the literature over the last 2 years [2,29] and is generally called the indirect land-use change (ILUC) effect. However, additional crop production can also be achieved by changes in land management (e.g. intensification). In many cases ILUC emissions are calculated as average yearly values over periods of 20 to 50 years (EU Directive for direct emissions). Typical emission values over the whole period are on average 300 to 1600 t CO_2 equivalent/ha for the conversion of forest to agricultural land, and 75 to 364 t CO_2 equivalent/ha for grassland or savannah [4,29,30]. Fritsche [31] presented an average value of 5 t CO_2 equivalent/ha per year. For regions with relatively more conversion of forests, this value might be higher. With the help of model calculations assessments are made for the area and type of land actually converted as the result of the production of a biofuel or any bioenergy product. This has to be compensated by the emission savings from biofuel use, in many cases varying between 2 and 20 t/ha per year [32]. Mandatory bioenergy production can lead to decreasing prices of crude oil, and thereby lead to an increase in crude oil and total energy consumption. This effect is rather uncertain, but could reach as much as 50% of potential gains [33]. Other calculations resulted in an extra indirect emission of about 30% from the reduction in direct emissions. So these indirect emissions are in the order of 10–40% of the emissions of the substituted fossil fuels [28].

Bioenergy is an important component of the renewable energy mix in the EU, helping to ensure a stable energy supply. The European Union has set itself the ambitious target to increase the share of renewable sources in final energy consumption to 20% by 2020 [34]. In 2010 bioenergy was the source of approximately 7.5% of energy used in the EU. This is foreseen by European Environment Agency (EEA) to rise to around 10% by 2020, or approximately half of the projected renewable energy output, according to EU Member States' National Renewable Energy Plans [35]. The EEA has revised its estimate of potential bioenergy production in the EU first published in 2006 [36], reducing the estimate by approximately 40% [37].

2. Material and methods

The economic impact of bioenergy is presented by conducting a meta-analysis contrasting and combining results from various studies, biomass supply scenarios and global models linked to land, water and energy use, and climate change in terms of food-energy-, environmental security. The combinations of following terms were used to search relevant studies: food-, energy- and environmental security, food demand, yield trends, renewable energy, biomass, biofuels, by-products for livestock feeding from biofuel production, land-use change, biofuels and the environment, sustainability requirements, climate change mitigation. In addition, we also conducted supplemental searches by examining bibliographies of articles for additional references. References of the paper covered the period 2001 to 2013. The variability in estimates of bioenergy supply based on the studies used in the meta-analysis are summarized in Table 2 (Section 3).

Results are potentially biased because studies might differ in their focus on potential or realized effects, their use of different baselines for comparisons and other background conditions. The literature on the impacts of bioenergy expansions is already substantial; however, the effects of biofuel production on land use and GHG emissions have received much less attention. Furthermore, there is a lack of available publications related to the feed value of increasing biofuels by-products, which are supposed to be credited with the area of cropland required to produce the amount of feed they substitute. In this study calculations have been made for the land required for cultivation of feedstocks adding by-products substituted for grains and oilseeds.

This study generally focuses on global bioenergy production, however, the European Union's policy objective of achieving 20% GHG emission reductions using 20% of renewables by the year 2020 is presented as well. The major challenge is that the increase in the cultivation of energy crops could conflict with the availability of land for food crops, therefore the introduction of next generation biofuels in the EU would be essential for guaranteeing energy and food security, and sufficient reduction in carbon emissions to meet the 20% target. For this analysis relevant publications of the European Community and experts of the Member States were used.

3. Results and discussion

Land use for food and feed are typically determined by global diet and agricultural yield improvements. Helping farmers lose less of their crops will be a key factor in promoting food security. Besides competition with food and feed, increased use of biomass also has its effects on land use and water availability. Due to high dependence of the global food sector on fossil fuels the volatility of energy markets can have a potentially significant impact on food prices leading to increasing food insecurity. Furthermore, increasing fossil fuels consumption will lead to greater greenhouse gas emissions.

Bioenergy has significant potential to mitigate greenhouse gases if resources are sustainably developed and efficient technologies are applied. The impacts and performance of biomass production and use are region- and site-specific. The precise quantification of greenhouse gas savings for specific systems is often hampered by lack of reliable data. Furthermore, different methods of quantification lead to variation in estimates of greenhouse gas savings. Nonetheless practically all bioenergy systems deliver large greenhouse gas savings if they replace fossil-based energy and if the bioenergy production emissions – including those arising due to land use change – are kept low.

Biomass for energy is only one option for land use among others, and markets for bioenergy feedstocks and agricultural commodities are closely linked. The direct land-use change effects of bioenergy production can be controlled through certification systems, wherever biomass is grown. Indirect land-use changes, however, are more difficult to identify. Most current biofuel production systems have significant reductions in greenhouse

gas emissions relative to the fossil fuels displaced, if no indirect land-use change effects are considered. The debate surrounding biomass in the food versus fuel competition has resulted in the fast development and implementation of sustainability criteria biomass and biofuels certification and standards as voluntary or mandatory systems reducing potential negative impacts associated with bioenergy production. Such criteria do not apply to conventional fossil fuels. A proliferation of standards increases the potential for inefficiencies in the market and abuses such as "shopping" for standards that meet particular criteria. Lack of international systems may cause market distortions instead of promoting the use of sustainable biofuels production. Production of "uncertified" biofuel feedstocks will continue and enter other markets in countries with lower standards or for non-biofuel applications that may not have the same standards.

The transport sector is responsible for about 20% of world primary energy demand. Transport biofuels are currently the fastest growing bioenergy sectors even as they represent around 3–4% of total road transport fuel and only 5% of total bioenergy consumption today. Most capacity expansion and financing need is expected for next generation biofuels in the longer term and strong competition from other renewable energy projects with lower risks (wind and solar) can be experienced. Liquid biofuels for transport are generating the most attention, although only a small fraction of biomass is used globally for biofuels production at present.

Changes in land use, principally those associated with deforestation and expansion of agricultural production for food, contribute about 15% of global emissions of greenhouse gas. Currently, less than 3% of global agricultural land is used for cultivating biofuel crops and land use change associated with bioenergy represents only around 1% of the total emissions caused by land-use change globally most of which are produced by changes in land use for food and fodder production, or other reasons. The proportion of global cropland used for biofuels is currently some 2.5% (40 million gross hectares) with wide differences among countries and regions. By adding by-products substituted for grains and oilseeds the land required for cultivation of feedstocks declines to 1.5% of the global crop area (net land requirement).

Biomass and biofuel markets are globalized but face tariffs and non-tariff trade barriers leading to low trade flows in bioenergy markets compared to fossil fuel markets. International trade includes conventional biofuels and feedstocks but in the long term lignocellulosic feedstock trade is likely to grow rapidly. The infrastructure to handle woody resources already exists in the pulp and paper industry and can be easily used for the biofuel industry. A key requirement for all biofuels to get access to the market will be compliance with international fuel quality standards.

3.1. Risks to food security

The expected changes of available productive land for food production includes three factors, land take for other purposes (urbanization, mining, traffic and energy infrastructure), the use of agricultural products for non-food purposes; land degradation through erosion, salinization, compactions etc. The processes may vary in the different regions, but the problem may be very decisive for any attempt of closing yield gaps and securing food security.

Growth of human population to 9 billion around 2050, continuing economic growth and transitions towards richer diets with a higher share of animal products in emerging economies will probably result in a growth of global food production by 60% [38,39]. These trajectories are not likely to result in the same growth rates in global demand for primary biomass and farmland area as the efficiency of human use of biomass as well as commercial agricultural yields have grown substantially in the last century [40] and are generally expected to continue to rise in the next decades [13,14]. In the past 40 years, the cropland area required to meet humanity's rising food demand grew by approximately 30%, despite substantial agricultural intensification [41]. A continuation of current yield trends until 2050 will not suffice to meet the rising global food demand without further growth of cropland areas [42].

Future agricultural production will have to rise faster than population growth largely on existing agricultural land. Improvements will thus have to come from sustainable intensification that makes effective use of land and water resources as well as not causing them harm. Regarding yield improvements, there seems to be a large theoretical potential for yield improvements throughout the world, especially in the developing countries, but there are still major uncertainties as to what proportion of this potential can be harvested. The increase in food demand is met to some extent by an increase of agricultural yields. Crop yields would continue to grow, but at a slower rate than in the past. On an average, annual growth would be about half that of the historical period: 0.8% per annum from 2005/2007 to 2050, against 1.7% per annum from 1961 to 2007. Nevertheless, agricultural production would still need to increase by 60% by 2050 to cope with a 30% increase in world population. This translates into additional production of 1 billion tonnes of cereals and 200 million t of meat a year by 2050 (compared with production in 2005/2007). The annual growth of crop yields at 1.1% is enough to produce the amount food needed, however, the challenge is to do that under resource constraint [43]. In addition to yield growth there will also be a slow expansion of agricultural land. Arable land would expand by 70 million ha (less than 5%), an expansion of about 120 million ha (12%) in developing countries being offset by a decline of 50 million ha (8%) in developed countries. Much of the suitable land not yet in use is concentrated in a few countries in Latin America and sub-Saharan Africa, not necessarily in Asia (with some 60% of the world's population) where it is most needed, and much is suitable for growing only a few crops, not necessarily those for which the demand is highest [43].

In addition to food security food stability is important as well. The key issue here is predictability. People want to eat every single day, and are prepared to shoulder significant extra costs to be more sure of this in advance. In fact, this risk aversion is one of the things that keep the very poor very poor, and also leads well meaning governments to adopt policies that perpetuate food insecurity.

The reduction of current yield losses caused by pests, pathogens and weeds are major challenges to agricultural production. Globally, an average of 35% of potential crop yield is lost to pre-harvest pests [44]. In addition to the pre-harvest losses transport, pre-processing, storage, processing, packaging, marketing and plate waste losses are relatively high. Roughly one-third of the edible parts of food produced for human consumption, gets lost or wasted globally. Food losses in industrialized countries are as high as in developing countries, but in developing countries more than 40% of the food losses occur at post harvest and processing levels, while in industrialized countries, more than 40% of the food losses occur at retail and consumer levels [45]. We can also save water and energy by reducing losses in the food chain.

Bioenergy may compete with the food sector, either directly, if food commodities are used as the energy source, or indirectly, if bioenergy crops are cultivated on soil that would otherwise be used for food production. Both effects may impact on food prices and food security if demand for the crops or for land is significantly large. This issue has typically been of concern for the biofuels sector, which uses mainly food crops. Increased biofuels production could also reduce water availability for food production,

as more water is diverted to production of biofuel feedstocks [46,47]. Until now, the price increases that this has led to seem to be limited for most crops, and the agricultural sector has responded by increasing production. There are exceptions, though, especially with crops where biofuel demand accounts for a significant share of total demand (e.g. maize, oilseeds, and sugar cane). Besides competition with food and feed, increased use of biomass also has its effects on other sectors. Forest-based industries (pulp and paper, building materials etc) for example, will be affected by the increased use of wood for energy conversion, both negatively and positively [48].

Competition for land may be limited, as production of feedstocks for advanced biofuels are expected to be grown mainly outside cultivated land, and that some 100 million ha would be sufficient to achieve the target biofuel share in world transport fuels in 2050 [49]. An important step in increasing biofuel production and sustainability is the competitive production of biofuels from (hemi)cellulose. Perennial crops and woody energy crops typically have higher yields than grain, and vegetable oil crop used for current biofuels. The extent of grassland and woodland with potential for lignocellulosic feedstocks is about 1.75 billion ha worldwide. However, much of this grass- and woodland provide food and wood for cooking and heating to local communities, or is in use as (extensive) grazing ground for livestock and only some 700 to 800 million ha of this land is suitable for economically viable lignocellulosic feedstock production [50].

Hence, it seems unrealistic to expect that yield growth of food crops would free up large areas currently used as croplands for planting energy crops. In the last century, yield growth and efficiency gains in biomass conversion and use kept growth rates of the human appropriation of net primary production lower than those of population and economic development. If current trends of agricultural intensification and livestock feeding efficiency growth are projected into the future, meeting global food demand might be achieved without reducing the amount of annual plant production remaining in ecosystems, but only in the absence of large-scale additional bioenergy production [40].

It was pointed out by Nogueira et al. [51] that the perception that expansion of bioenergy use will set serious competition with food is not accepted by many experts. According to FAO [52], more than 80% of the food/feed global future demand will be fulfilled by increment in productivity. In fact, between 1961 and 2009, global cropland grew by about 12% and agricultural production expanded by 150%, due to productivity gains. As a relevant outcome, the world food security situation is steadily improving, as indicated by a consistent rise of average food consumption per capita and the progressive reduction of undernourishment in the developing world [53].

Most models (7 out of 10) project an increase of cropland of 10–25% by 2050 compared to 2005 (under constant climate), but one model projects a decrease. Pasture land expands in some models, which increase the treat on natural vegetation further. Across all models most of the cropland expansion takes place in South America and sub-Saharan Africa. In general, the strongest differences in model results are related to differences in the costs of land expansion, the endogenous productivity responses, and the assumptions about potential cropland [54].

Total cropland (excluding abandoned land) increases from 1442 million ha in 2005 to 1770 million ha in 2095. In the scenario without forest conservation, cultivation of dedicated bioenergy crops increases total cropland to 1830 million ha, but forest exclusion limits total cropland to 1520 million ha in 2095. Simulation results reveal that in the scenario without forest conservation up to 29 Gt of additional cumulative CO_2 emissions from land use change due to the cultivation of dedicated bioenergy crops are likely to occur until 2095. These co-emissions are negligible in the scenario with forest conservation [27]. Increasing food and bioenergy production is possible through intensification and technological change on currently used agricultural land. An average global rate of yield increase of 0.6% per year is projected until 2095. This is equivalent to an increase in yields by the factor 1.8 in 100 years. Due to increasing bioenergy demand the global rate of yield increase would have to rise to 0.8% per year. The highest rate (0.9% per year until 2095) can be found in the forest conservation scenario, due to additional restrictions of land availability for agricultural expansion [27].

The food price index rises most strongly in Europe (22%) and in the the Newly Independent States of the Former Soviet Union (16%) until 2095 if climate change mitigation is taken into account and all suitable land is available for land expansion. But if forest conservation is considered, the food price index rises most prominently in Sub-Saharan Africa (82%), Latin America (73%) and Pacific Asia (52%) until 2095. In the scenario without forest conservation, strongest growth in the regional water price index, i.e. changes in shadow prices for irrigation water relative to the reference scenario until 2095, can be found in Latin America (210%), the Newly Independent States of the Former Soviet Union (170%) and Pacific Asia (130%). In this case, bioenergy cropland competes directly for irrigation water with other agricultural activities. The forest conservation scenario increases the regional water price index most heavily in Latin America (460%), Sub Saharan Africa (390%) and Pacific Asia (330%) [27].

3.2. Risks to energy security

The use of fossil fuels by agriculture has made a significant contribution to feeding the world over the last few decades. The food sector accounts for around 30% of global energy consumption and produces over 20% of global greenhouse gas (GHG) emissions. Around one-third of the food we produce, and the energy that is embedded in it, is lost or wasted. The energy embedded in global annual food losses is around 38% of the total final energy consumed by the whole food chain [55]. Due to high dependence of the global food sector on fossil fuels the volatility of energy markets can have a potentially significant impact on food prices, and this would have serious implications for food security and sustainable development [56]. Rising energy prices may cause spillovers into food markets leading to increasing food insecurity. Furthermore, any increase in the use of fossil fuels to boost production will lead to greater GHG emissions, which the global community has pledged to reduce [57].

Global primary energy demand is projected to rise from around in 2008 to 16,800 Mt oil equivalent in 2035 – an increase of over 35%. On a global basis, it is estimated that renewable energy accounted for 13% of the total 492 EJ (Exajoules)[1] or 12,300 million t oil equivalent (Mt) of primary energy supply in 2008 [58]. The largest contributor to renewable energy with 10% points was biomass. Hydropower represented 2% points, whereas other renewable energy sources accounted for 1% point (Fig. 1). The contribution of renewable energy to primary energy supply varies substantially by country and region.

Energy consumption is still increasing rapidly, with an approximate 540 EJ consumed at the primary energy level in 2010 [58]. Of this total 80% was provided by fossil fuels, about 10% by bioenergy mainly from wood combustion, 5.5% from nuclear, 2.2% from hydro, and 0.4% from other renewable energy sources. Biomass accounts for about 10% of global primary energy supply (54 EJ in 2010) and is the world's fourth largest source of energy (following oil, coal, and natural gas). The “traditional” share has been relatively stable for

[1] 1 EJ $=10^{18}$ J $=$ 23.88 million tons of oil equivalent (Mt).

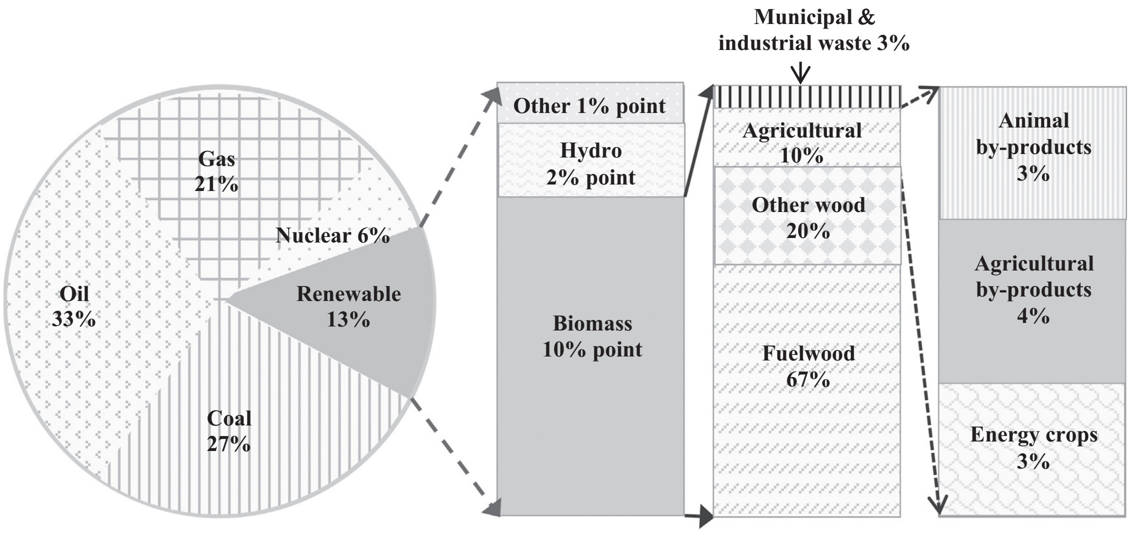

Fig. 1. World primary energy demand by fuel in 2008 [58].

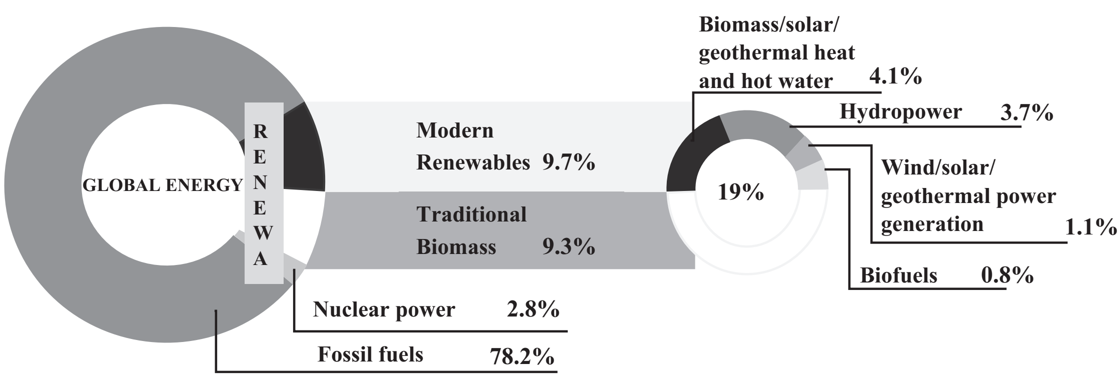

Fig. 2. Estimated renewable energy share of global final energy consumption in 2011 [60].

many years, while the "modern" share has grown since the late 1990s [58]. The world gets about 19% of its energy from renewables, including about 9.3% from traditional biomass and about 9.7% from modern renewables (Fig. 2). Useful heat energy from modern renewable sources accounted for an estimated 4.1% of total final energy use; hydropower made up about 3.7%; and an estimated 1.9% was provided by power from wind, solar, geothermal, and biomass, and by biofuels. The global share of electricity from renewables in 2010 was 20%, with over 70% of electricity provided by hydropower and the rest was produced using wind, solar, biomass and waste-to-power, geothermal, marine and small hydro technologies. The historic time for each energy source to grow from 1 to 10 EJ in primary energy production was 12 years for nuclear, 33 years for crude oil, 39 years for natural gas, 52 years for coal, and 59 years for hydro-power [59].

Heating accounted for the vast majority of biomass use, including heat produced from modern biomass and the traditional, contributing an estimated 6–7% of total global primary energy demand. The total volume of modern biomass consumption contributed an estimated 3–4% of global primary energy. Biomass used for energy purposes is derived from a number of sources. Residues from forests, wood processing, and food crops dominate. Short-rotation energy crops, grown on agricultural land specifically for energy purposes, currently provide about 3–4% of the total biomass resource consumed annually [58].

Traditional biomass is already a major source of energy in developing countries, primarily for heating and cooking in rural areas. The future trends in developing countries continue with a shift away from traditional biomass cookstoves to more modern forms of stoves and fuels, including efficient biomass cookstoves and stoves that burn biogas or biofuels. Technological progress also advanced the use of renewables in the rural heating and cooking sectors. Rural renewable energy markets show significant diversity, with the levels of electrification, access to clean cookstoves, financing models, actors, and support policies varying greatly among countries and regions. Government-driven electrification and grid extension programmes are still being adopted across the developing world.

The bioenergy sector is relatively complex because there are many forms of biomass resources; various solid, liquid, and gaseous bioenergy carriers; and numerous routes available for their conversion to useful energy services. Biomass markets often rely on informal structures, which make it difficult to formally track data and trends. Furthermore, national data collection is often carried out by multiple institutions that are not always well-coordinated, or that report contradictory findings. Consequently, national and global data on biomass use and bioenergy demand are relatively difficult to measure.

Future renewable energy shares are in the range of 15–20% in conservative scenarios, 30–45% in moderate scenarios, and 50–95%

in high-renewables scenarios. Attaining high shares of electricity is considered easiest, high shares of heating/cooling is the most difficult, and high shares of transport energy the most uncertain. All energy scenarios portray a mixture of energy supply technologies combined with energy demand growth and energy efficiency improvements [60].

3.2.1. The increasing competition for biomass: bioenergy potential

Overall, the global share of biomass has remained stable over the past two decades, but in recent years a sharp decline in share can be observed in China due to a rapid growth of total energy consumption and a steady increase of all types of biomass (for electricity, heat and biofuels) in the EU. The worldwide potential of bioenergy is limited because all land is multifunctional and land is also needed for food, feed, timber and fiber productions, as well as for nature conservation and climate protection. In addition, the use of biomass as an industrial feedstock (e.g. plastics) will become increasingly important. At present, some 55 EJ/year of bioenergy are produced globally. Modern forms of bioenergy in use in 2011 amounted to 23.6 EJ as heat, biofuel and electricity. An additional 31.4 EJ of traditional biomass was used very inefficiently for cooking/heating in poor rural areas, mainly in Africa [59].

According to the literature review, the global technical potential for bioenergy, considering also demand for other land-use, ranges from less than 50 EJ to 1500 EJ in 2050 (Table 1). Based on this diverse range of feedstocks, the technical potential for biomass is estimated to be possibly as high as 1500 EJ/year by 2050 [8]. However, most biomass supply scenarios that take into account sustainability constraints, indicate an annual potential between 200 and 500 EJ/year (excluding aquatic biomass owing to its early stage of development), representing 40% to 100% of the current global energy use [2]. Forestry and agricultural residues and other organic wastes (including municipal solid waste) would provide between 50 and 150 EJ/year, while the remainder would come from energy crops, surplus forest growth, and increased agricultural productivity (Fig. 3).

Projected world primary energy demand by 2050 is expected to be in the range of 600 to 1000 EJ/year compared to about 500 EJ in 2008. The expert assessment suggests potential deployment levels of bioenergy by 2050 in the range of 100–300 EJ/year. However, there are large uncertainties in this potential, such as market and policy conditions, and there is a strong dependence on the rate of improvements in the agricultural sector for food, fodder and fiber productions and forest products. The entire current global biomass harvest would be required to achieve a 200 EJ/year deployment level of bioenergy by 2050. Scenarios looking at the penetration of different low carbon energy sources indicate that future demand for bioenergy could be up to 250 EJ/year [61]. It is reasonable to assume that biomass could sustainably contribute between a quarter and a third of the future global energy mix.

The total annual aboveground net primary production (the net amount of carbon assimilated in a time period by vegetation) on the Earth's terrestrial surface is estimated to be about 35 Gt carbon, or 1260 EJ/year assuming an average carbon content of

Table 1
Statistical estimates of minimum and maximum values of global bioenergy potential (EJ/year).

Studies referring to 2050	Low range	High range
Smeets et al. [8]	215	1 272
IEA Bioenergy [2]	50	1 500
Dornburg et al. [11]	200	500
IPPC [12]	50	500
Haberl et al. [9]	160	270
Global Energy Assessment [13]	80	140

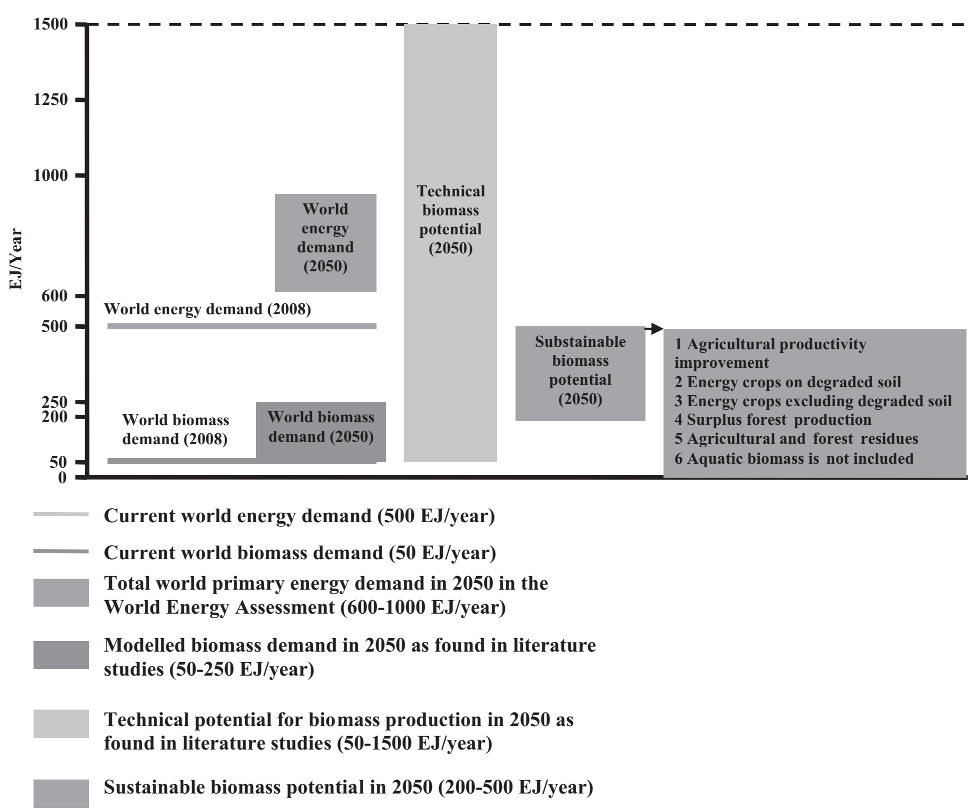

Fig. 3. Global bioenergy sources [58].

50% and 18 GJ/t average heating value [62], which can be compared to the current world primary energy supply of about 500 EJ/year [2]. All harvested biomass used for food, fodder, fiber and forest products, when expressed in equivalent heat content, equals 219 EJ/year [18]. The global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) corresponds to about 60 EJ/year and the global industrial roundwood production corresponds to 15 to 20 EJ/year [45].

Large estimates of bioenergy potentials are contingent on assuming large amounts of purpose-grown bioenergy because residue potentials are limited. Large energy crop potentials can only be justified by assuming the use of a large fraction of the Earth's surface or yields far exceeding current net primary production, or both [10]. The challenges associated with bioenergy result from the fact that plant growth is an inefficient way of converting sunlight into useable energy. The energy efficiency of photosynthesis is usually $<1\%$ under field conditions [63] – far below the efficiency of commercial solar photovoltaic cells of 12–20% [64]. For food, and many fiber and wood products, people have no alternative to using plants, but for energy the detour via photosynthesis may in many cases result in exceedingly high land demand. Developing more efficient methods of storing solar energy than relying on plants may hence be a more promising route. Given the biospheric constraints outlined above, it seems impossible that bioenergy could physically provide more than 250 EJ/year in 2050 [9,65,66], substantially below many published bioenergy projections. That figure could be the upper biophysical limit, however, realizing this potential would entail substantial trade-offs and risks [10]. 250 EJ/year equals 20–30% of global primary energy demand, assuming the range of energy demand scenarios in the Global Energy Assessment [13]. Reaching such a level of supply would require roughly a doubling of global biomass harvest in less than four decades and would result in massive increases in humanity's pressures on land ecosystems [66]. Large-scale promotion of bioenergy could result in economic incentives to divert land from food production to bioenergy which puts the world's poor at risk, driving up hunger and inequality. Can international policies prevent such adverse effects and instead foster sustainable production and consumption of bioenergy at sustainable levels?

The argument that solar photovoltaic cells (PV) are a better way to use solar energy than photosynthesis is very questionable [51,67]. The use of PV generated electricity requires solving the problem of storing energy which is still uncertain. In addition to that, solar power systems present strong seasonal and daily variability. As a result the capacity factor of solar systems is around 25% at best. In bioenergy systems, the solar radiation is naturally stored as chemical energy in the biomass and further in the biofuel, allowing full dispatchability. As a consequence, the current and prospective prices of bioelectricity and sustainably produced biofuels are competitive with regards to the photovoltaic alternative in many cases [56]. To understand the problem of bioenergy we should put it in the wider context of agricultural production and use of land: a total of 1553 Mha of land was in use for agricultural production in 2011, it was 1371 Mha in 1961, an increase of 182 Mha in 50 years over pastures, deforested (in some cases) and degraded lands [68].

Without forest conservation, bioenergy demand increases up to about 300 EJ in 2095 with a demand of about 100 EJ in 2055. This demand scenario is a result of the economic interplay between the agricultural and the energy sector where simulated bioenergy prices are rising to 7 US$ per GJ in 2095. For this specific scenario, biomass from dedicated bioenergy crops will contribute 25% to the total global demand for primary energy carriers. However, forest exclusion for the purpose of biodiversity conservation and climate change mitigation affects the availability of cost-efficient biomass for energy production significantly. The amount of bioenergy supplied is reduced to about 70 EJ in 2055 and 270 EJ in 2095 in the scenario with 100% forest conservation [27].

In the EU final energy consumption is about 50 EJ/year with a 8.5% share of bioenergy. The estimate of potential bioenergy production in the EU first published in 2006 [36] was revised due to changes in scientific understanding, the changed EU policy framework and accounting for economic factors, reducing the estimate by approximately 40% (EEA 2013). The study [37] concludes that significant amounts of biomass can technically be available to support ambitious renewable energy targets, even if strict environmental constraints are applied. The bioenergy potential in 2030 represents around 15–16% of the projected primary energy requirements of the EU-25 in 2030 compared to a 4% share of bioenergy in 2003 and to a 8.5% share in 2010. In contrast, the environmentally compatible energy cropping scenario developed by the EEA for 2020 includes a much larger share of perennial grasses and short rotation trees (under coppice management) in total energy crop mix at about 40% of the total [37]. Different energy cropping systems can vary hugely in their productivity, as well as in environmental impacts. High-yielding systems with efficient conversion can deliver more than 20 times more energy compared to low-yielding inefficient systems using the same land area. The countries with the largest estimated agricultural bioenergy potential in 2020 are France, Germany, Spain, Italy, Poland and Romania.

Different biomass-to-energy conversion technologies vary significantly in their efficiency. For example, generating electricity by burning pure biomass is only approximately 30–35% efficient, while burning the same material to produce heat is usually more than 85% efficient. In general, using bioenergy for heat and power is a considerably more efficient way of reducing greenhouse gas emissions, compared to using bioenergy for transport fuel. Extensively using mature trees for energy purposes may have a negative effect on the climate, due to the long time it takes for the trees to regrow and re-capture the CO_2 that is released when wood is used for energy. This carbon debt does not arise if bioenergy uses other forest biomass instead, for example branches left over from forest harvesting by-products or waste products from timber and paper production. Using organic waste and agricultural or forestry residues as feedstock is more resource efficient than many other types of feedstock, as it does not add pressure on land and water resources and offers very high greenhouse gas savings.

Availability of land for non-food crops will be determined by increased yield potential, reducing losses and wastes along the food chain and lower inputs. However, these volumes will remain limited relative to total energy and transport sector fuel demand. Limited biomass resources will be allocated to the sector (materials, chemicals, and energy) that is most able to afford them. This will depend on the price of existing fossil fuel products and the relative cost of converting biomass into substitute final fuels such as bio-derived electricity, ethanol blends, biodiesel and bio-derived jet fuel. It will also depend on factors such as cost of alternative fuel and energy sources, government policies including excise rates, and the emission intensity of each sector.

The sustainable use of residues and wastes for bioenergy, which do not require any new agricultural land and present limited or zero environmental risks, needs to be encouraged and promoted globally. Several factors may discourage the use of these "lower-risk" resources. Using residues and surplus forest growth, and establishing energy crop plantations on currently unused land, may prove more expensive than creating large-scale energy plantations on arable land. In the case of residues, opportunity costs can occur, and the scattered distribution of residues may render it difficult in some places to recover them [49]. Whatever is actually realised will depend on the cost competitiveness of bioenergy and on future policy frameworks, such as greenhouse gas emission reduction targets. The uptake of biomass depends on biomass production costs – US $4/GJ is often regarded as an upper limit if bioenergy is to be widely deployed today in all sectors – logistics, and resource and environmental issues [56].

3.2.2. Transport biofuel market

The transport sector is responsible for about 20% of world primary energy demand. Liquid biofuels continue to make a small but growing contribution to transport fuel demand worldwide, currently providing about 3% (2.6 EJ) of global road transport fuels. They also are seeing small but increasing use in the aviation and marine sectors [69].

Growth in biofuels markets, investment, and new plant construction has slowed in several countries in response to a number of factors: policy uncertainty, increased competition for feedstock, impacts of drought conditions on crop productivity, concerns about competition with food production for land and water resources, and concerns about the sustainability of production more broadly [70]. The total annual capacity of the approximately 650 ethanol plants operating globally is around 100 billion litres, but many facilities are operating below nameplate capacity and others have closed due to fluctuating demand and concerns about the environmental sustainability of the product. The number of operating biodiesel facilities is more difficult to assess as there are many small plants, often using waste cooking oils to produce biodiesel for local or personal vehicle use. The aviation industry has continued to evaluate closely the increasing uptake of advanced biofuels, including those produced from algae. Their interest stems from the current high dependence on petroleum fuels; uncertain long-term supplies; and the lack of other suitable fuel alternatives [71].

Currently, around 80% of the global production of liquid biofuels is in the form of ethanol. In 2012 global fuel ethanol production reached 86 billion liters, global biodiesel production amounted to 18 million t, or 20 billion liters (Figs. 4 and 5). In 2012 the United States was the world's largest producer of biofuels,

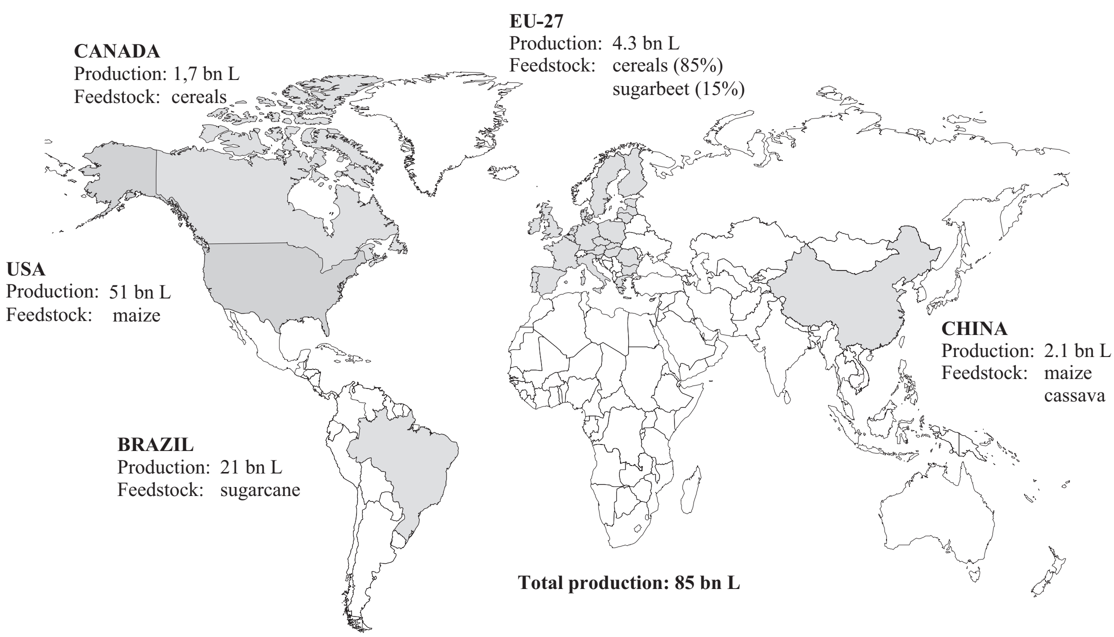

Fig. 4. Word fuel ethanol production, 2012 [73].

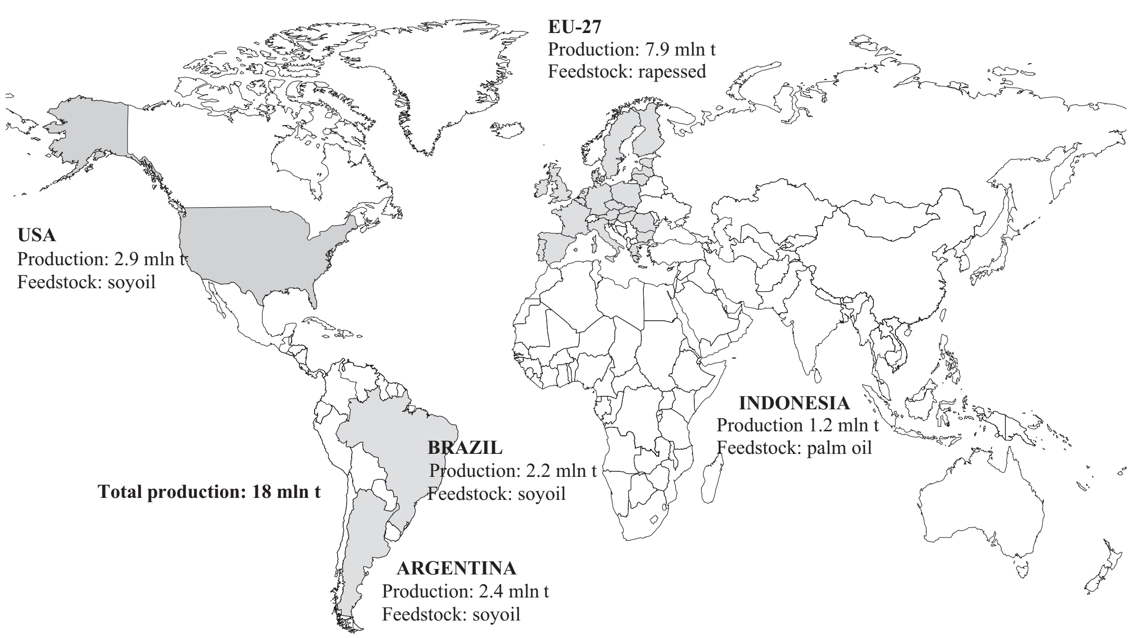

Fig. 5. World biodiesel production, 2012 [73].

followed by Brazil and the European Union. The two world's top ethanol producers, the U.S. and Brazil, accounted for around 85% of total production. The U.S. is the world's largest bioethanol producer. In 2012, it produced 51 billion liters of ethanol and accounted for 60% of global production. In Brazil fuel ethanol production reached 21 billion liters and in the EU 4.3 billion liters in 2012. China, at 2.1 billion liters, remained Asia's largest ethanol producer [73]. Global biodiesel production amounted to 18 million t (20.5 billion liters) in 2012. Biodiesel production is far less concentrated than ethanol. The European Union remained the center of global biodiesel production, with 7.9 million t liters and representing 43% of total output in 2012. Biodiesel accounted for the vast majority of biofuels consumed in the EU, but growth in the region continued to slow. The slowdown of biodiesel output in many countries was due to increased competition with relatively cheap imports from outside the EU. This trend is leading to plant closures from reduced domestic production requirements, an expansion of tariffs on imports, and increases in some blending mandates [72].

However, production of both ethanol and biodiesel is increasing rapidly in Asia. Thailand and India increased both its ethanol and biodiesel production. Biofuels production in Africa is still very limited, but markets are slowly expanding. On a regional basis, North America continued to lead in ethanol production, and Europe in the production of biodiesel.

In 2012, U.S. production of advanced biofuels from lignocellulosic feedstocks reached 2 million liters, however, these volume remains only a small proportion of the original U.S. mandate under the Renewable Fuel Standard (RFS) that was subsequently waived. China also made progress on advanced biofuels in 2012, with around 3 million liters of ethanol produced from corn cobs and used in blends with gasoline. The EU has several demonstration plants in operation but each has produced only small volumes to date [73].

Farm and community-scale biogas plants continue to be manufactured and installed for treating wet waste biomass products, especially in Europe where almost 12,000 plants operated in 2012. In addition, 2250 sewage sludge facilities are operating in Europe; approximately 2% of these plants upgrade the biogas to higher-quality biomethane for use as a vehicle fuel or for injection into the gas grid [74]. Biomethane is now used widely as a vehicle fuel in Europe. There were around 1.7 million gas-powered vehicles operating in Europe in 2012 but most used natural gas. During 2012 in Germany the share of biomethane in natural gas increased from 6% to more than 15%, and the number of fueling stations selling 100% biomethane more than tripled. Further, 10% of the natural gas vehicles in Germany used compressed biomethane fuel instead of compressed natural gas methane [75].

Several airlines have demonstrated biofuel use in aircraft test flights in recent years, but experts noted that alternative aviation fuels are not available in sufficient quantities for use beyond small shares. Some scenarios ponder a major role for hydrogen in both shipping and aviation in the long term, but few model such by 2050. Most scenarios show some role for biofuels in shipping and aviation by 2050, but typically much less than for road transport. The IEA (2012) found that projections for biofuels in aviation ranged from a few percent to 30% by 2050 [76].

The aviation industry supports the efforts to reach a new post-Kyoto deal by ensuring a global commitment to fight climate change effectively, promoting research program for renewable energy sources such as sustainable biofuels for aviation and respecting the Chicago Convention (fair treatment of airlines). Aviation is responsible for 2% man made CO_2 emissions and produces 8% of global GDP. Over 40 years the focus on innovation has led to 70% reduced aviation fuel consumption and related CO_2 emissions. Aviation requires a global scheme developed through the International Civil Aviation Organization (ICAO). The industry supports market based measures. Aviation biofuels are supposed to compete on equal basis as land transport. They also need to be competitive with current kerosene prices as airlines cannot sustain a premium for biofuels, however, the industry recognizes short term price challenge. Carbon pricing and rising jet fuel price provides an opportunity. Biodiesel production poses a risk because it is more attractive than aviation biofuel. The industry has made progress in achieving technical fuel approval focusing on second generation biofuels that avoid negative environment impacts. Certification is not anymore an issue, technically feasible and certified fuels with no engine or aircraft modifications include: maximum 50–50% blend for SPK (Synthetic Parraffinic Kerosene) derived by Fisher-Tropsch process BtL (Biomass to Liquid) fuels, maximum 50–50% blend HRJ (Hydrotreated Renewable Jet) fuels derived from hydrotreated plant oils. Drop-in fuels are fully compatible and interchangeable with JetA1. Other fuels are also in the pipeline of certification process. In 2011 American Society for Testing and Materials (ASTM), an international standards organization gave the airlines the go-ahead to incorporate biofuels into as much as 50% of the total fuel they use on passenger flights. They certified advanced biofuels as meeting the ASTM International specification for bio-derived aviation fuels, "Hydroprocessed Esters and Fatty Acids" (HEFA) fuel [77].

In the end of 2011 the European Court of Justice confirmed the validity of the European Emissions Trading Scheme (EU ETS) directive that includes aviation activities in the emissions trading scheme since. The EU is not bound by the Chicago Convention because it is not a party to that convention. Its second point relating. The Court observed that the parties to the Kyoto Protocol may pursue limitation or reduction of emissions from aviation fuels outside the member states of ICAO. In relation to the operator of an aircraft being required to surrender emission allowances calculated on the basis of the whole of the flight, the Court pointed out that EU legislature may permit air transport to be carried out in its territory only on condition that operators comply with the criteria that have been established by the EU. The Court concluded by stating that the uniform application of the scheme to all flights which depart from or arrive at a European airport is consistent with the provisions of the Open Skies Agreement designed to prohibit discriminatory treatment between American and European operators. It means that nothing changes; the airlines should keep on complying with EU ETS as they have done so far. The EU have already stated that they are negotiating the possibility of agreeing "equivalent measures" with several non-EU States and if they should come to an agreement that might have a bearing on the inbound EU sector with those nations, but not on the ex-EU or intra-EU sectors [78].

In the EU Renewable Energy Directive (RED) transposition in several member states only includes incentives for ground transport. Biojetfuel suppliers should qualify for tradable certificates within incentive regimes provided for by national applications of the RED, such as Renewable Transport Fuel Certificate (RTFC) in the UK. Exclusion of aviation prevents a level playing field with road transport. Unlike aviation other sectors have alternative technologies to liquid fuel like (e.g. electric) and a significant timing advantage versus aircraft in engine technology adoption. The roadmap of the European Commission in 2011 gave a positive signal with clear milestones which targets an annual production of 2 million t of sustainably produced biofuel (4% of EU fuel consumption) for aviation by 2020. The European Commission, Airbus with leading European airlines and European biofuel producers have launched the Biofuel Flightpath initiative to try and speed up the commercialization of aviation biofuels in Europe. Priority is now for full scale production and life cycle assessment [77]. In 2011 Boeing, an active Roundtable on Sustainable Biofuels (RSB)

member, announced the launch of a partnership with the Roundtable on Sustainable Biofuels called the Sustainable Biomass Consortium (SBC), a research initiative focused on increasing collaboration between voluntary standards and regulatory requirements for biomass used to create jet fuel and bioenergy for other sectors. Boeing, Airbus, and Embraer were collaborating on biofuel initiatives in 2012, and SkyNRG began buying pre-treated biofuels derived from used cooking oils and further refining them into aviation-grade fuel [72].

British Airways (BA) and Solena produce a waste-to-biofuels plant in East London, or nearby, with several potential sites identified in the area. The investment will be $350 million and initially produce enough fuel per day to fill 80 tanker trucks. This represents around 2% of BA's fuel needs in the London area and this initial batch will be used exclusively at the nearby London City airport. Despite the huge investment the business case is made on the existence of the waste used avoiding a $100 per tonne landfill tax. Elsewhere a Dutch company SkyNRG is supplying several airlines' trials of biofuel flights with waste oils from catering use and then converted to biofuel. Lufthansa has a partnership with Finnish company Neste and is using a 50% biofuel/kerosene mix on all flights of one dedicated A320 aircraft between Frankfurt and Hamburg for several months, with no adverse events and no apparent differences in engine performance or exhaust deposits [77]. However, the main question is how to get sufficient quantities of biofuel and at the right price? Given the technical approval (ASTM D7566) of the 50% biofuel/kerosene mix in 2012 there has certainly been a noticeable increase in interest, and a forecast in the UK Sustainable Aviation Roadmap that by 2050 sustainable biofuels will contribute an 18% reduction in aviation emissions [77].

Mandatory bioenergy production can lead to decreasing prices of crude oil, and thereby eventually lead to an increase in crude oil and total energy consumption. This so-called rebound effect can reduce the possible gain from biofuels, substantially, especially if not all sectors are facing some form of climate policy, or not all countries participate in climate change policies.

3.2.3. Financing advanced biofuel

Investment in renewable power and fuels (including small hydro-electric projects) was $244 billion in 2012, down 12% from the previous year's record figure of $279 billion. Global investment in renewable energy decreased in 2012, but investment expanded significantly in developing countries. Global investment decreased in response to economic and policy-related uncertainties in some traditional markets, as well as to falling technology costs, which had a positive effect on capacity installations. Renewable energy is spreading to new regions and countries and becoming increasingly affordable in developing and developed countries alike [79].

Most capacity expansion – and thus financing need – is expected for next generation biofuels in the longer term (except from sugarcane-based ethanol in Brazil). Ultimately, these biofuels should be produced at lower costs than the current generation but feedstock and technology poses time and money-related barriers since the new supply chains, feedstock and technology are unproven and investment capital expenditure is very high. The roll-out of large-scale next generation facilities will be a slow process. The key to unlock financing is control or co-operation in the supply chain in addition to lower costs. Cellulosic ethanol plants are still considerably more expensive to build than corn ethanol plants, by a factor of 2–3 in higher investment costs. So costs will have to decline significantly, although cellulosic feedstocks are cheaper, so capital investment costs give only part of the picture. Costs can be mitigated through a variety of possible processes, including hybrid processes combining biochemical and thermo-chemical conversion [70].

General capital constraints make competion for financing from other renewable energy projects (e.g. wind farms) stronger. A strong and clear business case that eliminates or reduces cash flow uncertainties is needed. For example, wind energy often has the advantage of a fixed feed-in-tariff. Pre-requisite for long-term survival is a largely integrated supply chain via contracts, ownership and agreements. Key success factors of any bioenergy project are logistics and location, price risk management, feedstock supply (easy and assured access), off take (easy and assured contracts), capacity utilization (benchmark is 75%), experienced management and compliance with sustainability requirements. The annual value of renewable energy capacity installed will double in real terms to $395 billion in 2020, rising to $460 billion in 2030, compared with $195 billion in 2010 – according to analysis company Bloomberg New Energy Finance [80]. Spending on new renewable energy capacity will total $7 trillion over the next 20 years. The solar and wind sectors will continue to expand with a combined share of 70% in total money spent on renewable energy projects but biofuel is projected to reach a share of just 8% or US $510 billion in total spending. Banks are cautious to lend money which means that more sources of capital are needed. Strong competition from other renewable energy projects with lower (perceived) risks (specifically wind) can be experienced. Fuels should be taxed directly proportional to their energy content since competition balances supply and demand. Market prices including CO_2 costs would allocate resources most efficiently.

3.2.4. Renewable energy and transport policies

At least 138 countries had renewable energy targets by the end of 2012. Some 120 countries around the world have some type of policy and/or target to promote renewable energy, more than two-thirds of which are developing countries or emerging economies. The number of policies keeps growing year by year. Renewable energy support policies were identified in 127 countries, more than two-thirds of which are developing countries or emerging economies. Most policies to support renewable energy target the power sector, with feed-in tariffs (FITs) and renewable portfolio standards (RPSs) used most frequently. About 30 countries were getting 20% or more of their total energy from renewables, and some as high as 50%. Some countries have long-term policy targets that will put them squarely in the “high renewables” domain by 2030 or 2050, such as Denmark (100%) and Germany (60%). Outside of Europe, a diverse group of at least 20 other countries target energy shares in the 2020–2030 time frame that range from 10% to 50%, including Algeria, China, Indonesia, Jamaica, Jordan, Madagascar, Mali, Mauritius, Samoa, Senegal, South Africa, Thailand, Turkey, Ukraine, and Vietnam [59].

Thousands of cities and towns around the world have developed their own plans and policies to advance renewable energy. To achieve ambitious targets, local governments adopted a range of measures, including FITs or technology-specific capacity targets; fiscal incentives to support renewable energy deployment; and new building codes and standards, including solar heat mandates. Others developed renewable district heating and cooling systems; promoted the use of renewably powered electric transport; formed consortia to fund projects; or advanced advocacy and information sharing. Several cities are working with their national governments to promote renewable energy, while others have begun to organize from the bottom up. In Europe, 1116 new cities and towns joined the Covenant of Mayors in 2012, committing to a 20% CO_2 reduction target and to plans for climate mitigation, energy efficiency, and renewable energy [59].

The passenger vehicle fleet will double to 1.7 billion in 2035 [70]. Common biofuel policies include biofuel subsidies, tax exemptions, or blending mandates. Biofuel blend mandates were

identified at the national level in 27 countries and in 27 states/provinces. Despite increasing pressure in major markets such as Europe and the United States, due to growing debate over the overall sustainability of first generation biofuels, regulatory policies promoting the use of biofuels existed in at least 49 countries in 2012 [59].

To drive development of biofuels that provide considerable emission savings and at the same time are socially and environmentally acceptable, support measures need to be based on the sustainable performance of biofuels. Recent years have also seen increased attention to biofuels sustainability and environmental standards. Another approach is to directly link financial support to life-cycle CO_2-emission reductions (calculated with a standard life-cycle analysis methodology agreed on internationally) to support those biofuels that perform best in terms of CO_2 savings. Neither specific advanced biofuel quota, nor performance based support measures on their own seem to be effective to address the higher production costs of advanced biofuels in the short term. Specific transitional measures may thus be needed to support the introduction of the new technologies. Financial incentives, for instance a tax incentive or perhaps analogous to feed-in tariffs for electricity, could be coupled to the use of co-products such as waste heat to promote efficient use of by-products.

A key requirement for all biofuels to get access to the market will be compliance with international fuel quality standards. This will ensure vehicle and infrastructure compatibility among different regions and promote consumer acceptance for new fuels. End-use infrastructure requirements need also to be addressed to avoid bottlenecks caused by incompatibility with deployed biofuels. The ethanol “blending wall” – the limiting of ethanol in gasoline to 10% to 15% because of vehicle compatibility constraints – is one example of potential infrastructure bottlenecks that need to be addressed. Evolution of fuel specifications and new fuel grades are taken into account in the developing of future vehicles, such as compatibility of vehicles in the fleet with higher biofuels blends or new limits for existing specifications. Backward compatibility of fuel changes is a very difficult issue because it is extremely difficult to cover all the vehicle generations and models combined with reliability risks for the customers and a risk for vehicle manufacturers in meeting legal commitments (CO_2 emissions) and furthermore it is costly. Automotive manufacturers need sufficient protection for the existing fleet at any point in time and a sufficient lead-time and clear fuel specifications for the future. At least 5 years lead-time should enable car industry to adapt to new fuel standards. Electric vehicles get much attention and incentives but they still face many barriers. They seem to be viable for light vehicles and short distances [72].

Introduction of flex-fuel vehicles (FFV) and high-level ethanol blends is a suitable measure to avoid infrastructure incompatibility issues for ethanol, as has been successfully demonstrated in Brazil, the US and the EU. Introduced in the market in 2003, flex vehicles became a commercial success in Brazil, reaching almost 100% share of all new cars and light vehicle sales today. Most of the cars on the road in the U.S. can run on blends of up to 15% ethanol, and the use of 10% and 15% ethanol gasoline is mandated in several U.S. states and cities. Well over 90% of U.S. gasoline is blended with ethanol. In the EU Member States (Germany and France) the biofuel “blending wall” has been increased up to 10%. Policy measures may be required, such as obligations for retailers to provide high-level biofuel blends (e.g. E85) or tax incentives for FFVs. Ford was the first manufacturer offering in 2001 FFVs in Europe and began to develop market also beyond Sweden. In contrast to Brazil (and Sweden) there are no significant incentives for customers to buy FFVs because the production costs of ethanol exceed gasoline costs. Reason for that is primarily the different feedstock used in Europe versus Brazil. The market of FFVs will remain a niche without substantial and stable net fuel price benefits.

The challenge is the limited backwards fleet capability. In 2008 the German government proposed to increase both, biodiesel and bioethanol blend limit from 5% v/v each to 10% v/v. However, after incompatibility concerns of vehicle manufacturers with B10 occurred in 2009 biodiesel blend limit 7% v/v was agreed. The complete vehicle stock in Germany is B7 capable. In 2011 E10 was introduced but only approximately 93% of vehicle stock is E10 capable. Vehicle compatibility lists needed to be issued because protection grade fuel (E5) for 7% of vehicle owners was required. While B7 introduction was easy, E10 introduction is still a nightmare. Customers are unsettled about the right fuel for their car. Furthermore, customers widely boycott E10 leading to much less consumption of E10 than expected. Lesson learned from the experience in Germany is that wide spread blending of usual market fuel with bio-components ideally requires 100% backwards compatibility with vehicle stock. Vehicle compatibility less than 100% requires compatibility lists, which is a politically very complicated process. Communication is key in managing changes. On the other hand blending can lead to new test method demands. Lack of capable test methods during fuel introduction can lead to severe fuel quality issues [72].

3.2.5. Global trade in biomass and bioenergy

The development of international markets for bioenergy has become an essential driver to develop available biomass resources and market potential, which are currently underutilized in many world regions. In the short term, trade will include conventional biofuels and feedstocks, but after 2020, lignocellulosic feedstock trade is likely to grow rapidly and supply large advanced biofuel plants in coastal locations. The infrastructure to handle woody resources (both forest residues and plantation grown wood) already exists in the pulp and paper industry and can be easily used for the biofuel industry. Pelletisation, pyrolysis or torrefaction will become increasingly important since they increase the energy density and thus tradability of lignocellulosic feedstocks (e.g. residues). These intermediate products are relatively homogeneous and thus more suitable for conversion to biofuels. Scale and efficiency improvements will reduce biofuel production costs over time.

Biomass and biofuel markets have globalized over the last decades but are still immature and face tariffs and non-tariff trade barriers leading to radical and mostly undesired shifts in international trade flows. These are aggravated by the fact that international trade flows in bioenergy markets are still relatively low compared to fossil fuel markets. Interactions between national policies, import tariffs and non-tariff trade barriers are also complicated by the cross-links of bioenergy markets to food- or industrial commodities markets. Trade will become increasingly important to promote biofuel production and meet blending mandates, as well as to balance demand and supply fluctuations among different regions. International trade in biomass and biofuels has become much more important in the last decade, with roughly 5% of biofuels (fuel ethanol and biodiesel only) traded internationally and one-third of all pellet production for energy use in 2010. Data related to fuel bioethanol trade are imprecise on account of the various potential end uses of ethanol (i.e., fuel, industrial and beverage use) and also because of the lack of proper codes for biofuels in global trade statistics [81].

Bio-methane, fuelwood, charcoal, briquettes, and agricultural residues are mainly traded locally; whereas wood pellets, wood chips, biodiesel, and ethanol are traded both nationally and internationally [82]. Demand for modern biomass is driving increased international trade, particularly for biofuels and wood

pellets. In global production and transport of wood pellets exceeded 22 million t, and in 2012 about 8.2 million t of pellets were traded internationally, 40% of pellets were shipped from North America to Europe [59,82]. Smaller, more-compact wood pellets account for only 1–2% of total global solid biomass demand, but they account for a large share of solid biomass trade. The energy content of traded solid biomass fuels (excluding charcoal) is about twice that of net trade in biofuels. Demand continues to increase due to the pellets' higher energy density and lower moisture content relative to wood chips; ease of handling; convenience of use; suitability for co-firing in coal-fired power plants; and the option of automatic control options in small heat plants. About two-thirds of pellet production is used in small heat plants and one-third in larger power plants [83].

3.3. Risks to the environment

3.3.1. Land use change and GHG emission

The bioenergy sector is relatively complex because there are many forms of biomass resources; various solid, liquid, and gaseous bioenergy carriers; and numerous routes available for their conversion to useful energy services. Biomass markets often rely on informal structures, which makes it difficult to formally track data and trends. Furthermore, national data collection is often carried out by multiple institutions that are not always well-coordinated, or that report contradictory findings. Consequently, national and global data on biomass use and bioenergy demand are relatively difficult to measure and, as a result, relatively uncertain. The total area of land used for bioenergy crops is difficult to quantify accurately because of large data gaps. Furthermore, some energy crops are grown for competing non-energy uses. For example, ethanol production volumes from sugar cane fluctuate with the sugar commodity market price, and, in the case of palm oil, only around 15% of the total produced is used for biodiesel.

The production of biomass feedstock and its conversion to useful energy have varying environmental and socioeconomic impacts that depend on a number of factors, as with other renewables. The sustainability of biomass production, associated land use change, feedstock competition, trade restrictions, and impacts of biofuels produced from food crops such as corn remain under review and could affect future demand. Ethanol production in the United States, for example, consumes about 15% of annual global corn production, raising concerns about its impact on food supply.

The cultivation of energy crops requires land. In case agricultural land is used, it replaces other crops. The possible options for growing feedstocks to produce bioenergy: use of currently productive land or/and the conversion of unproductive land. These are direct land-use effects. In case of the conversion of unproductive land (land without any agricultural or forestry production, such as nature areas) all effects are direct effects, since there is a one to one relation between the feedstock production and the land use changes and its related emissions and no additional land use effect regarding productive land is assumed to occur here. Direct effects are the effects that can be directly and exclusively linked to the production– consumption chain of the bioenergy product. During the entire life cycle (production and consumption chain) of a product resources are used and emissions occur. The changes in these resources are all regarded as direct effects.

The direct effects can be directly linked to and therefore controlled by the actors in the production chain. This makes criteria and regulations for direct effects effective. The present EU criteria include direct GHG emissions and direct effects of land use. Direct GHG emissions have been subject of intense discussion, resulting in the restriction that, to be included in the 10% target, GHG emission savings from the use of biofuels and bioliquids should be at least 35%, compared to fossil fuels. This threshold will rise to 50% as of 2017, and to 60% as of 2018 for new plants. Only direct LUC emission is accounted and indirect LUC emission is not calculated. For biofuels in transport the most common boundary of the life cycle is from the well (the biomass growth) to the wheel (application of the fuel). This well-to-wheel method is applied to determine direct GHG emissions. Forests and wetlands are excluded for feedstock production, as are other high carbon or high biodiversity land use types [34]. Similar requirements exist for the U.S. Renewable Fuel Standard [84] and California's state standard. Brazil also adopted new sustainability policies for sugarcane ethanol in 2009 [85]. Only advanced biofuels, particularly from agricultural wastes and from crops on marginal lands like switch grass, would ensure future sustainability.

In case of cultivation on currently productive land (e.g. agricultural land, formerly used for crop production for food, feed and fiber, including forest production), the original crop would have to be produced elsewhere or our consumption habits must change. This is the starting point for the indirect effects. Indirect effects are the effects that are caused by the introduction of a bioenergy product, but cannot be directly linked to the production chain. Apart from the direct effects of the biofuels production chains, there would be many other differences between a world with and a world without biofuels. These differences are the indirect effects. The production chain of a bio-energy product is just one of many production–consumption chains. These chains interact with dynamic global systems, such as the economic system, the climate system, ecosystems and the agricultural system. Examples are higher prices for (non-biofuel) food products, nature conversion for food production, lower feed and oil prices. The numerous interactions imply that every indirect effect in its part is a cause of other effects and so on, although the impact is becoming smaller and smaller. However, a final equilibrium is often not reached, because these dynamic systems are changing continuously and so are the indirect effects.

Land use decisions are affected by many factors from local to global in scope, including public policy, prices of agricultural commodities, prices of petroleum, and land values. Profitability of specific land uses and the benefits of competing uses are also key influences on land use decision-making. Decision-makers who choose to produce biomass must consider land use and potentially also land use change (LUC). Land use is management of land resources for economic benefit and includes tillage, maintenance and harvest activities as well as conservation practices. Land use change includes conversion of native ecosystems into agricultural use, as well as switching from one crop type to another. Also included in the LUC category is diversion of food crops grown primarily for food into bioenergy feedstock use, for example, corn grain.

Biomass demand is thought to be a local or regional level influence on land use decision-making. However, competing uses, such as production of conventional commodity crops for example, are driven by complex global financial and trade systems. Land use decisions in response to biomass and bioenergy demand, then, are coupled with local and global economies. Native and managed ecosystems are sources of financial benefit when materials are removed from these systems and exchanged in markets. Native ecosystems and managed ecosystems also provide many benefits which indirectly affect humans. Water and nutrient cycling are but two examples of the benefits ecosystems provide that have no direct economic value. Land use and LUC associated with biomass production can increase or decrease the direct and indirect benefits of native and managed ecosystems. Whether land use and LUC increase or decrease these benefits depends on the type and amount of benefits occurring prior to LUC.

The necessity to reduce global GHG emissions to a level consistent with limiting global warming to 2 °C motivate an intensified search for renewable low-carbon energy. Biomass is an attractive option, due to its relatively low costs, its storability, and also because it can be rather easily substituted for fossil fuels in many important applications such as heat, power and mobility [64]. The establishment of the required new energy technologies and associated infrastructure will in itself lead to GHG emissions, implying that a portion of the emission space allowed within the GHG target will need to be invested for energy system transformation [49].

Results reveal that the energy sector uses about 100 EJ globally in 2055 and up to 300 EJ in the year 2095 from dedicated energy crops, if all suitable land for agricultural production was made available for land expansion. However, cultivation of bioenergy crops has several effects: it increases cropland expansion; it takes over a huge share in total cropland; it is mainly located in areas that today are occupied by intact ecosystems; and it increases CO_2 emissions from deforestation. Thus, converting intact ecosystems, such as tropical rainforests or open woodlands, which store large amounts of carbon and belong to the most diverse terrestrial ecosystems, counteracts global climate and biodiversity protection goals. For bioenergy to make a real net contribution to climate change mitigation, intact forests have to be protected. By the exclusion of intact and frontier forests the reduced land pool available for agricultural use would have to be compensated by higher rates of technological change (0.9% per year until 2095) at additional costs to fulfill the demand for bioenergy. From 1970 to 1995 average yield growth across all crops was about 1.3% annually but growth rates have declined in the most recent decade [27].

Due to rising bioenergy prices, restrictions for land availability decrease bioenergy use in the energy system in 2055 considerably to about 70 EJ. But in the long run (until 2095) the use of biomass in the energy system is competitive, mainly due to the option of generating negative emissions in the energy system by using CCS. Reason is the difficulty to supply the transportation sector with low-carbon fuels. Bioenergy is partly converted to fuels and partly to electricity, both in combination with CCS. The resulting negative emissions compensate for higher gross emissions from fossil fuels. However, with respect to the importance of CCS for the contribution of bioenergy to climate change mitigation one needs to consider that the availability of this technology is still uncertain and not yet proven on a large scale. CCS will require huge infrastructure developments, in particular a pipeline network similar to the existing gas transport infrastructure, and new storage capacities [27].

The cost-effective and sustainable contribution of bioenergy from dedicated energy crops to climate change mitigation can be enhanced or reduced if other assumptions are taken into account. On the one hand, other biomass resources such as the use of agricultural and forest residues, ranging from very low estimates to around 100 EJ could be considered. However, competing applications of biomass for soil improvement or animal feed could reduce the potential of residues for bioenergy application to the lower end of the range. On the other hand, assumption on global availability of cellulosic biomass without any trade restrictions may overestimate calculated bioenergy potentials. Even though the volume of biomass trade for food, feed and fiber has grown rapidly in recent years, trade of biomass for bioenergy is in its initial phases, with wood pellets, ethanol, and palm oil being typical examples to meet growing demand. Transportation of cellulosic biomass for bioenergy production could become more efficient by converting biomass into charcoal and thus increasing its energy content [27].

Bioenergy from dedicated ligno-cellulosic energy crops is likely to be a cost-efficient contribution to the future energy mix. Without considering co-emissions from deforestation, biodiversity issues, and impacts on food and water security, the biomass resource potential could deliver a considerable amount of the world's primary energy demand up to 2095. Restrictions on land availability, by protecting untouched tropical forests and other high-carbon ecosystems, are likely to reduce bioenergy potentials significantly in the medium run, but less so in the long run. Most likely, forest conservation combined with large-scale cultivation of dedicated bioenergy for climate change mitigation will generate conflicts with respect to food supply and water resource management. Integrated policies for energy production, land use and water management are therefore needed to steer the potential contribution of bioenergy to the future energy mix, without neglecting the side effects on land-use-related GHG emissions, biodiversity conservation, food and water security [27].

The transport sector is currently responsible for 23% of energy-related CO_2 emissions. To achieve the projected target of 50% reduction in energy-related CO_2 emissions by 2050 from 2005 levels sustainably produced biofuels production must provide 27% of total transport fuel. Reductions in transport emissions contribute considerably to achieving overall targets. India and China show significant increases because of rapidly growing vehicle fleets. Vehicle efficiency improvements account for one-third of emissions reduction in the transport sector; the use of biofuels is the second-largest contributor, together with electrification of the fleet accounting for 20% (2.1 Gt CO_2-equivalent) of emissions saving [86].

The role of bioenergy systems in reducing GHG emissions needs to be evaluated by comparison with the energy systems they replace using life-cycle assessment (LCA) methodology. The precise quantification of GHG savings for specific systems is often hampered by lack of reliable data. Furthermore, different methods of quantification lead to variation in estimates of GHG savings. Nonetheless practically all bioenergy systems deliver large GHG savings if they replace fossil-based energy and if the bioenergy production emissions – including those arising due to land use change – are kept low. Currently available values indicate a high GHG mitigation potential of 60–120%,[2] similar to the 70–110% mitigation level of sugarcane ethanol and better than most current biofuels [2]. However, these values do not include the impact of land use change (LUC)[3] that can have considerable negative impact on the lifecycle emissions of advanced biofuels and also negatively impact biodiversity.

To ensure sustainable production of advanced biofuels, it is therefore important to assess and minimize potential indirect LUC caused by the cultivation of dedicated energy crops. This deserves a careful mapping and planning of land use, in order to identify which areas (if any) can be potentially used for bioenergy crops. Brazil is the only emerging country that has initiated the agro-ecological sugarcane zoning program (ZAE Cana) to direct available land to the production of biofuel feedstock in order to stop deforestation and indirect land use change [86]. The program constrains the areas in which sugar cane production can be expanded by increasing cattle density, without the need to convert new land to pasture. The program is enforced by limiting access to development funds for sugar cane growers and sugar mill/ethanol plant owners that do not comply with the regulations. The program currently focuses on sugarcane, but it could also be applied to other biofuel feedstocks.

[2] An improvement higher than 100% is possible because of the benefits of co-products (notably power and heat).

[3] Two types of land use change (LUC) exist: direct LUC occurs when biofuel feedstocks replace native forest for example; indirect LUC (iLUC) occurs when biofuel feedstocks replace other crops that are then grown on land with high carbon stocks.

Changes in land use, principally those associated with deforestation and expansion of agricultural production for food, contribute about 15% of global emissions of GHG. Currently, less than 3% of global agricultural land is used for cultivating biofuel crops and LUC associated with bioenergy represents only around 1% of the total emissions caused by land-use change globally most of which are produced by changes in land use for food and fodder production, or other reasons [87]. Indirect land-use changes, however, are more difficult to identify and model explicitly in GHG balances. Most current biofuel production systems have significant reductions in GHG emissions relative to the fossil fuels displaced, if no indirect LUC effects are considered.

3.3.2. Sustainability criteria for bioenergy

Many efforts are under way to develop sustainability criteria and standards that aim to provide assurance about overall sustainability of biofuels. International initiatives include the Global Bioenergy Partnership, the Roundtable on Sustainable Biofuels, the International Organization for Standardization and the International Sustainability and Carbon Certification System. There are also initiatives looking at standards for the sustainable production of specific agricultural products, such as the Roundtable for Sustainable Palm Oil, the Roundtable for Responsible Soy and the Better Sugarcane Initiative. Development of standards or criteria will push bioenergy production to lower emissions and higher efficiency than today's systems. The standards aim at ensuring sustainable production of feedstocks, regardless of their final uses (be it for food, material or biofuel production), and can thus help to ensure sustainable production throughout the whole sector, rather than for the feedstock specifically dedicated to biofuel production. Some policies have been adopted during recent years that include binding sustainability standards for biofuels.

The EU has introduced regulations under the Renewable Energy Directive (RED) that lay down sustainability criteria that biofuels must meet before being eligible to contribute to the binding national targets that each Member State must attain by 2020 [34]. The EU is the global frontrunner on sustainability, other continents may follow. In December 2008, the EU adopted a new policy on biofuels as part of a new RED [34], an ingredient of the EU Climate and Energy Package. This directive details on the EU objective of a 20% overall share of energy from renewable sources by 2020 and includes 10% energy from renewable sources in transport. Bioenergy is an important option for meeting these goals, and specifically biofuels for transport. The debate on the sustainability of biofuels set off relatively late during the process of political decision-making. This discussion also influenced the negotiations on the renewed Fuel Quality Directive [88], which includes a 10% reduction target for greenhouse gas (GHG) emissions for 2020 for transport fuels. Under time pressure and in close cooperation between the European institutions it was decided to include a set of sustainability criteria for biofuels, both in the Renewable Energy Directive and the Fuel Quality Directive. But this set of criteria does not cover all issues and there is no guarantee for sustainability. However, the ILUC emission factor was criticized for lacking a proper scientific foundation and it was decided to keep the effects of ILUC out of the sustainability criteria included in the Directives. In order to count towards the RED target, biofuels must provide 35% GHG emissions saving compared to fossil fuels. This threshold will rise to 50% as of 2017, and to 60% as of 2018 for new plants. However, there is a loophole as only direct LUC emission is accounted and indirect LUC emission is not calculated.

The focus of the sustainability criteria in the EU Directive is on biofuels for transport, particularly liquid biofuels, such as ethanol or biodiesel, and gaseous fuels, such as biomethane. Furthermore, the criteria also apply to bioliquids, generally used in other applications such as for heating, cooling and electricity. Not all bio-energy products are included as the criteria in the directive do not concern biomass as a resource for the chemical industry, and solid biomass and gaseous products used in other applications than for transport. Biomass is converted into many intermediate and end products. Usually, the first processing step converts the biomass into products which are easier to handle than conventional feedstocks. Examples are pellets, vegetable oils, pyrolysis oil, ethanol, syngas and biomethane. Some of them are end products themselves (e.g. bioethanol), others are converted further into products such as biodiesel, biohydrogen, bioplastics, biomethane, and bio-electricity. Many of the products have more than one application; for example, biomethane, which is used for transport and for heating. Another example is the use of ethanol for transport and in the chemical industry. In both examples, the EU criteria only hold for the transport application.

In the United States, the Environmental Protection Agency (EPA) is responsible for the Renewable Fuel Standard program [84]. This establishes specific annual volume requirements for renewable fuels, which rise to 36 billion gallons by 2022. These regulatory requirements apply to domestic and foreign producers and importers of renewable fuel used in the US. Advanced biofuels and cellulosic biofuels must demonstrate that they meet minimum GHG reduction standards of 50% and 60% respectively, based on a life-cycle assessment (including indirect land-use change) in comparison with the petroleum fuels they displace. In 2010, the EPA designated Brazilian sugarcane ethanol as an advanced biofuel due to its 61% reduction of total life cycle greenhouse gas emissions, including direct indirect land use change emissions [85]. In Switzerland the Federal Act on Mineral Oil mandates a 40% GHG reduction of biofuels in order to qualify for tax benefits.

Sustainability criteria and biomass and biofuels certification have been developed in increasing numbers in recent years as voluntary or mandatory systems; such criteria, so far, do not apply to conventional fossil fuels. The registered several dozens of initiatives worldwide to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels, as well as agriculture and forestry, can lead to a fragmentation of efforts. A proliferation of standards increases the potential for confusion, inefficiencies in the market and abuses such as “shopping” for standards that meet particular criteria. Such disparities may act as a discouragement for producers to make the necessary investments to meet high standards. There is a risk that in the short term a multitude of different and partially incompatible systems will arise, creating trade barriers [89]. If they are not developed globally or with clear rules for mutual recognition, such a multitude of systems could potentially become a major barrier for international bioenergy trade instead of promoting the use of sustainable biofuels production. In addition, lack of international systems may cause market distortions. Production of “uncertified” biofuel feedstocks will continue and enter other markets in countries with lower standards or for non-biofuel applications that may not have the same standards. The existence of a “two-tier” system would result in failure to achieve the safeguards envisaged (particularly for LUC and socioeconomic impacts).

3.3.3. Substitution of traditional animal feed with co-products of biofuel production

The bioethanol share in total grains demand – i.e. corn, wheat and other coarse grains – is about 8% of global production. By adding the feed value of ethanol by-product dried distillers's grains and solubles (DDGS), the net shares decline by one third to slightly above 5%. The bulk of the worldwide use of grains in

alcohol production comprises corn in the USA and China. However, an increase in the offtake of wheat for fuel ethanol can also be observed in Canada and the EU. The fuel ethanol sector, mainly in the US, accounts for 15% (net 10%) of global corn consumption and 20% of global sugar cane production. The biodiesel share in rapeseed, soybean and palm oil demand is around 10% of global vegetable oil production. The share of waste biodiesel feedstocks such as animal fat and used cooking oil increased to 15% in total biodiesel output [72].

It is important to highlight that for a long time growth in consumption of corn outside the US outstripped the growth in supply outside the US, and annual growth in US corn exports made up the difference. With the rise of corn based ethanol in the US after 2003, US corn exports remained constant instead of growing each year, and world corn prices increased accordingly. Ultimately the main solution needs to include increasing productivity in the rest of the world.

In many cases, crops are resources for more products than only bioenergy. Crops, such as rapeseed, (for biodiesel) or wheat, corn (for ethanol) also deliver co-products with high protein content. These protein rich products can be applied as animal feed, substituting other feeds, such as soymeal, the most important protein source for livestock production. When soymeal is substituted, less land for soybean cultivation is needed. For the energy crops wheat and rapeseed, depending on assumptions about the yields and the protein contents of the co-products, the reduction of land-use for soybean production can be 50% to 100% of the land needed for the wheat and rapeseed. This substitution reduces the indirect land use and therefore the impact of indirect land use change and intensification is substantially. Additionally, it is not yet clear what the real potential is of replacing soymeal, because of quality restrictions. The impact of the co-products on land use can be included. An increase in the supply of this animal feed from co-products could lead to a decrease in prices for animal feed, and subsequently to an increase in consumption of meat and dairy products. The opposite effect could occur, if waste products from agriculture or the food industry, which are used as animal feed in the present situation, are turned into a resource for fuel production instead. In those cases, feed has to be produced elsewhere and even ILUC effects cannot be excluded.

Corn used to produce ethanol also produces co-products such as DDGS, corn gluten feed (CGF), corn gluten meal (CGM) and/or corn oil. Due to the lack of production and global trade statistics data related to the co-products of biofuel production are imprecise. The U.S. ethanol industry produced about 36 million metric tonnes of DDGS in the 2010/11 marketing year. Nearly 25% of U.S. ethanol feed output is exported to countries around the world to feed livestock and poultry. Bioethanol is used to a far lesser extent in Europe, where about 4 million t of DDGS is produced a year. DDGS is still priced based on the price of corn. Identifying corn demand for ethanol should take in to account that DDGS is used as a high-value animal feed. DDGS and other ethanol feed products significantly reduce the need for corn and soybean meal in animal feed rations. The DDGS produced by U.S. ethanol plants have important implications for discussions regarding ethanol's impact on feed grains availability, feed prices, land use effects, and the GHG impacts of producing corn ethanol [90].

DDGS can be used to replace some soybean meal as well as corn in livestock and poultry rations. The digestive systems of ruminant animals (cattle, sheep, and goats) are well suited for using DDGS. For cattles, DDGS replaces corn or both corn and soybean meal up to around 40%. Digestive systems of hogs and poultry are less suited for feeding high levels of DDGS, although it can be used at up to 15% to 20% of their rations. About 90% of DDGS is used in the ruminant sector and only 10% in the hog and poultry sectors [90].

Over the past several years, DDGS has been one of the most economically competitive sources of energy and proteins available on the world feed market. Feed market impacts of increased corn use for ethanol are smaller than that indicated by the total amount of corn used for ethanol production because of DDGS. By reporting only the gross usage of corn for ethanol, the implication was that all the corn going into ethanol production resulted in fuel ethanol. According to the conventional assumption ethanol producers return a full one-third of the corn processed back to the feeding sector which is the difference between the gross and net volume of corn used for ethanol. However, in aggregate, a metric tonne of DDGS can replace, on average, 1.22 metric t of feed consisting of corn and soybean meal in the United States. In fact, the amount of feed (corn and soybean meal) replaced by the DDGS represents 38% a weight basis) of the corn used in the associated ethanol production process for a given crop year. One of the reasons that one tonne of DDGS can replace more than one tonne of conventional feed is that its energy and protein contents are concentrated. Only the starch portion of the corn kernel is converted to ethanol, while the protein, fat, fiber and other components are concentrated and passed through the process to the DDGS. If co-products are taken into account the net use of feedstocks decline [90].

More complicated, but no less important, is the impact of DDGS on land use change and the GHG emissions associated with corn ethanol production. Most existing biofuel regulations significantly undervalue the contribution of DDGS when assessing the net GHG impacts of corn ethanol assuming that one metric tonne of DDGS replaces only one metric tonne of corn, with no substitution of soybean meal. The importance of DDGS is being undervalued by the regulatory agencies requiring a GHG assessment of ethanol. In the future accurate DDGS accounting is of increasing importance.

There is a limited demand for glycerin, the by-product of biodiesel production for a number of food, beverage, personal care and oral products, as well as pharmaceutical and other industrial uses. The mandated future levels of biodiesel use in the EU and U.S. could create substantial excess supplies of glycerin for these markets. To deal with that potential problem and to create additional markets for the by-product of biodiesel, research at different countries has found that glycerin can be used effectively in livestock rations to replace fossil-based glycerin.

In 2010 about 20 million gross hectares of grains, sugar cane and cassava for fuel ethanol production and 20 million gross hectares of oilseed feedstock was needed for biodiesel production (Table 2). The proportion of global cropland used for biofuels is currently some 2.5% with wide differences among countries and regions. In the US some 8% of cropland is dedicated to biofuel production, however, 20–35% of corn and soybean area is used for biofuel production. In the EU 5–6% of cropland is used for biofuel production. In Brazil biofuel is just requiring 3% (ethanol 1.5%) of all cropland (included pastureland) available in the country even if more than 50% of sugar cane area (20% of global area) is used for ethanol production [authors's calculation].

The biofuel production processes give rise to co-products which are largely suitable as animal feed. By-products are supposed to be credited with the area of cropland required to produce the amount of feed they substitute. In the cases of grains and oilseeds, DDGS, CGF/CGM and oil cakes (mainly rapeseed and soybean cake/meal) substitute grain and soybean as feed. It means that not all the grains used for ethanol production should be subtracted from the supplies since some 35% is returned to the feed sector in the form of co-products (mainly DDGS) so the land required for feedstock production declines to 15 million ha. In case of biodiesel production 50–60% of rapeseed (rapeseed cake/meal) and 80% of soybean (soybean meal) is returned to the feed sector and the net land requirement decrease to around 6 million ha.

Table 2
Area requirements for biofuel production [91].

	Bioethanol	Cultivated area (M ha)	Biodiesel	Cultivated area (M ha)
North America	Corn	13.0	Soybean, palm oil, rapeseed	5.0
South/Central America	Sugar cane	4.5	Soybean, castor- oil plant, palm oil, jathropha	9.0
Europe/Eurasia	Wheat, sugar beet	1.5	Rapeseed, soybean, sunflower	6.0
Rest of the world	Cassava, sorghum, cellulose	1.0	Palm oil, coconut, jatropha	0.5
Total		**20.0**		**20.5**

By adding co-products substituted for corn and soybean meal the net hectares needed for fuel ethanol decline to 21 million [authors' calculation]. By adding by-products substituted for grains and oilseeds the land required for cultivation of feedstocks declines to 1.5% of the global crop area (net land requirement).

Based on the land-use efficiencies land use for biofuel production would need to increase from 40 million ha (21 million ha net land requirement by adding co-products substituted for grains and oilseeds) to around 100 million ha in 2050. This corresponds to an increase from 2.5% of total arable land today to around 6% in 2050. This expansion would include some cropland, as well as pastures and currently unused land, the latter in particular for production of lignocellulosic biomass [49].

4. Conclusions

The role of renewable sources continues to be the fastest-growing power source in the global power mix. In the near future global renewable electricity generation is expected to surpass that from natural gas. The increased population density, coupled with changes in dietary habits in developing countries towards high quality food is projected to increase demand for food production by 60% by 2050. In addition unprecedented development is taking place, especially in areas that have traditionally had very low per capita demand on fossil resources. The need to increase agricultural productivity and efficiency in developed as well as in developing countries is now widely accepted. Producing more food sustainably requires crops that make better use of limited resources including land, water and fertiliser. The comparison between high input agriculture which cannot be sustained and agro ecology does not help at all because it is not the core of the debate anymore. The core is whether existing knowledge on agro ecological practices can achieve this yield growth rate and if not whether investing in research and innovation focusing on this stream of practices rather than intensification can contribute to achieve them. In addition to food security food stability is important as well and the key issue here is predictability. With increasing demands of energy it has become apparent that the continued emissions of greenhouse gases and loss of carbon sinks are influencing the world climate.

The increasing demand for suitable land in which this biomass needs to grow competes with the need for food production. This is causing conflicts between land use for food and those for producing bioenergy crops. These problems will be amplified by the change in land productivity caused by climate change (erosion, water stress, increasing soil salinity, and others more). Policies for promoting biomass as an alternative energy source will need to take these potential land use conflicts into account. The global potential for biomass energy production is large in absolute terms, but it is far not enough to replace the current energy usage. Increasing biomass energy production beyond a certain level would have significant effects on land use and conventional agricultural markets.

Recent estimates on the potential global ligno-cellulosic bioenergy supply range from less than 100 EJ/year – to 1500 EJ year – for 2050. But besides biomass availability, future application of biomass for energy production is also determined by its interaction with other energy options and relative costs. In other energy scenarios, bioenergy use is projected to be in the order of 150–400 EJ in the year 2100. These studies give first insights into the potential contribution of bioenergy to the future energy mix, however, future yield improvements and land use expansion remain unclear. Besides uncertainties of cost-effective use of bioenergy application, large-scale energy crop production may create conflicts with other sustainability aspects, like food and water security or climate change mitigation and biodiversity conservation. More biofuels on the market could reduce the oil prices resulting in more economic activity. This might lead to extra emissions equal to 10–40% of the fossil fuel emissions.

Globally, advanced biofuels capacity is expected to expand only slowly, though the first commercial-scale plants in the United States and Europe were recently commissioned. While the United States should remain the largest producer, technical and economic challenges related to blending more than 10% ethanol in the gasoline pool raise uncertainty over the outlook. In Brazil, more optimistic sugar cane harvest conditions and new government support measures should drive continued growth, though the ethanol sector there still faces financial difficulties. High feedstock prices and poor margins continue to challenge biofuel producers in Europe.

A huge number of countries have blending mandates and/or targets for future shares of biofuels in transport. Nevertheless, long-term transport shares are the most challenging to project, and the most uncertain, because the range of possible vehicle technologies and fuel types in the future is very broad, future oil prices are uncertain, and technology progress from vehicle batteries to advanced biofuels, remains unpredictable. These factors create uncertainty about what future transport systems look like. Several scenarios project shares of transport fuels, however, projections vary widely.

Most biomass used today is simply burned for heat and power. The second most common process is anaerobic conversion to biogas. Increased production of biogas from sewage plants, manure, and organic waste, and cheaper biogas plants made with new materials can be expected. The use of biomass heating technologies will also gain impetus. A fundamental difference between most renewable energy generation and fossil and nuclear power is the cost ratio between capital and operating costs. The marginal costs of most renewables are low and often prevail over conventional power generation on spot markets. Bio-refineries could become part of the food system by 2020, and lead to integrated bio-based industries for food, fuels, chemicals, textiles, paper, and other products.

A breakthrough in biomass demand could come as biomass becomes a mainstream commodity in commercial markets in standard forms like pellets or bio-heating oil (from pyrolysis/torrefaction). Pellets may become a widespread commodity,

efficiently transported internationally. It is questionable how much biomass could be produced given competition for land and food. On the other hand there are no serious limits because of the huge resources available from agricultural and forest wastes, and from new approaches to growing biomass crops on surplus land.

The international bioenergy market is expected to have a wide range of suppliers from several world regions and the importation of bioenergy is therefore not affected by the same geopolitical concerns as are oil and natural gas. The use of bioenergy resources and biomass trade would generally contribute to the diversification of the energy mix. A regime for the growing trade of solid biomass (pellets and chips) and liquid biofuel is needed with the adoption of sustainability criteria in the international arena. A trend toward harmonization of standards and certificates can be expected to continue in the future, however, the number of standards is continuously changing to take in to account the scientific advancements in the design and production of new materials and ever changing applications.

The science of global climate change indicates an overall warming trend for the Earth as a whole in association with rising levels of GHGs. While natural sources effect the concentrations of GHGs over time, global scientific consensus indicates that human sources of GHGs also contribute to global climate change. To-date, there is no scientific consensus on whether bioenergy as a whole contributes to or abates global climate change. Rather, scientific evidence appears to indicate that “it depends”. First generation biofuel systems, such as ethanol made from corn grain, tend to emit more GHGs than cellulosic ethanol systems, particularly CO_2. Compared to perennial biomass production, corn cropping requires more fertilizer and pesticide inputs, and results in greater soil disturbance leading to land use-induced carbon emissions. Moreover, when agricultural commodity prices are high, marginal lands and lands set-aside for conservation purposes tend to be converted into row-crops such as corn and thus lead to LUC-induced CO_2 emissions. In comparison, second and third generation biofuels offer greater potential for GHG mitigation through use of cellulosic feedstocks which originate from production systems that tend to have less land-use related GHG emissions. Additionally, biochar – the co-product of pyrolysis is carbon rich and stable, and when added to soil it serves as a long-term carbon bank. While second, third, and even fourth generation biofuel systems potentially reduce GHGs they are not yet widely available at commercial scales and future demand is uncertain.

Bioenergy can have positive and negative ecological and environmental impacts, and the overall net impact can be either positive or negative. Many of the ecological and environmental impacts of bioenergy are associated with land use and land use change in connection to biomass production. Bioenergy-related land use decisions may affect local, regional and global ecological and environmental systems. Bioenergy is often considered carbon neutral, as the carbon dioxide released in combustion is assumed to be compensated by the CO_2 absorbed during plant growth. However, indirect land use change can negate any greenhouse gas savings from biofuel production based on energy crops. This is due to the displacement of crop production onto previously unused land, which can lead to the conversion of forests and savannah to agriculture. Such land use change harms biodiversity and increases greenhouse gas emissions. Two indirect effects of bioenergy production received much attention in public debate: indirect land use leading to GHG emissions and biodiversity loss, and indirect impact on food prices determining the availability of food for the poor.

There is no fixed indirect emission factor for a specific bioenergy product. Indirect effects of bioenergy products, such as biofuels are not fixed characteristic of the bioenergy product, but the result of the interaction with dynamic global economic and physical systems. Furthermore, indirect GHG emissions bear a scientific uncertainty and vary in time. Reported emissions from indirect land-use change (ILUC) caused by bio-energy products are in the order of 30 to more than 100% compared to the fossil fuel emissions. Intensification of agriculture is a way to minimize indirect land use change. However, if higher yields are the result of increasing fertiliser use only, indirect emissions might occur. So, fertiliser use efficiency should be improved with the potential to further reduce GHG-emissions. Indirect effects on biodiversity are strongly related to land conversion. Reducing GHG-emissions by substituting fossil fuel by a bioenergy product can result in less negative impact on biodiversity from climate change on the long term. However, it will indeed take a long period (more than 100 years) to compensate for the short term loss of nature due to direct land conversion for the energy crop. In case of indirect land use this period for compensation can be shortened by stimulating global agricultural intensification, especially an increase of fertiliser use efficiency.

In the EU bioenergy should be produced in line with EU objectives to use resources more efficiently. This means reducing the land and other resources needed to produce each unit of bioenergy and avoiding environmental harm from bioenergy production. The most efficient energy use of biomass is for heating and electricity as well as advanced biofuels, also called second generation biofuels. First generation transport biofuels, for example, biodiesel based on oilseed rape or ethanol from wheat/maize, are far less efficient use of resources. The current energy crop mix in the EU is not favorable to the environment, a broader mix of crops could reduce environmental impacts. For example, perennial crops (energy grasses or short rotation willow plantations) would enhance ecosystem services provided by farmland – such as flood prevention and water filtration.

The biofuel production processes give rise to co-products which are largely suitable as animal feed. By-products are supposed to be credited with the area of cropland required to produce the amount of feed they substitute. If co-products are taken into account the net use of feedstocks decline. Moreover, it is important to include the co-products in GHG assessment, because of their potential impact on the overall emissions. Most existing biofuel regulations significantly undervalue the contribution of co-products when assessing the net GHG impacts of biofuel production. In the future accurate co-products accounting is of increasing importance.

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